Saving SOHO

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http://soho.nascom.nasa.gov/operations/Recovery/

Prologue

GSFC: June 25 1998 (07:12 UT)

The following E-mail was issued by the Operations Team at NASA/GSFC:

"After the planned momentum management, while still in thruster mode, the Attitude and Orbit Control Subsystem (AOCS) switched into ESR (Emergency Sun Re-acquisition) mode on 24 June at 23:16, due to a procedure problem. On 25 June at 02:35 a second ESR occurred during standard ESR recovery, triggered by a roll rate anomaly; the reason is unclear. Some time later, at 04:38, a third ESR triggered by a fine Sun-pointing anomaly and all telemetry was lost.

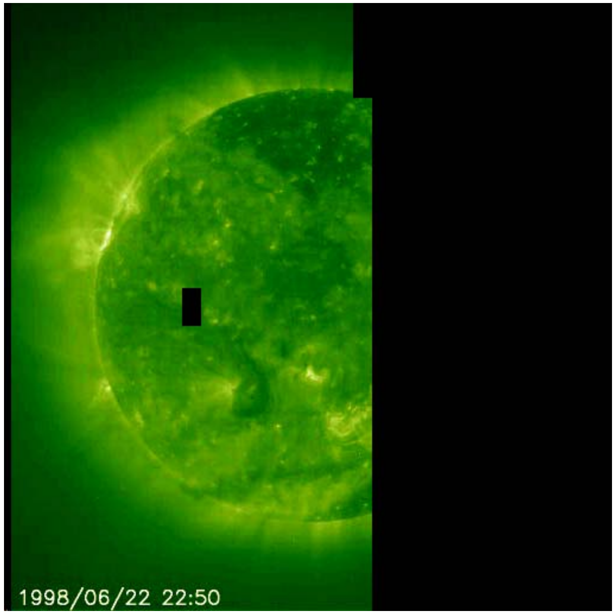
ESTEC – we have a problem!

Our worst nightmare was beginning to unfold:

SOHO WAS LOST IN SPACE

June 24 1998 - SOHO in Trouble

- Several compounding errors in pre-programmed command sequences and an erroneous real-time decision left SOHO without gyroscopes, which are necessary for autonomous on-board roll control.
- SOHO went into a spin with increasing ‘coning’
- Loss of attitude control ultimately resulted in loss of power, telemetry and thermal control.



Last images from SOHO/EIT

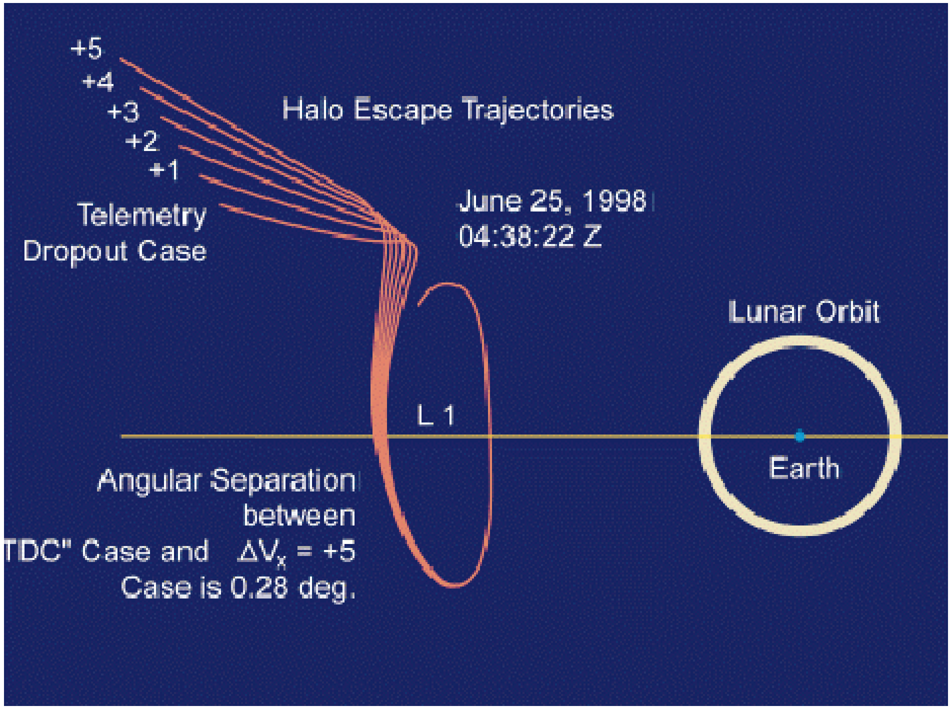
SOHO spins out of control

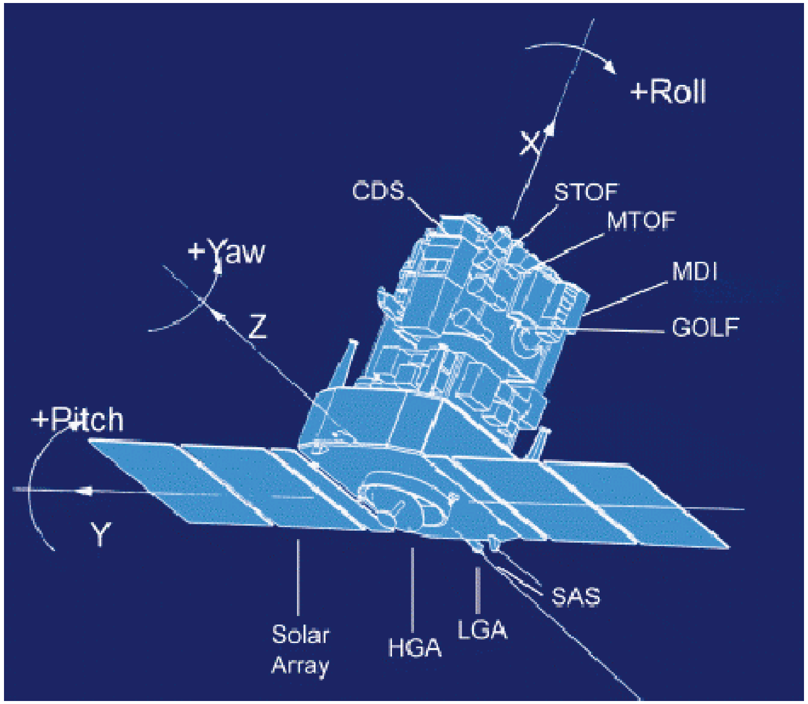
Search for the Downlink Carrier

- Within a few hours after the loss of telemetry, a team of ESA and MMS engineers was formed to assess the situation and establish procedures to re-establish contact with the S/C
- ESA ground stations in Perth (Australia), Vilspa (Spain) and Redu (Belgium) supported the search for a downlink signal
- First members of the Recovery Team left Europe on 26 June
- Full Recovery Team at GSFC on 28 June
  - Flight Dynamics simulations to understand what happened and predict present attitude
  - Thermal models
  - Orbit predictions
  - Efforts to optimize command loads to switch on transmitter

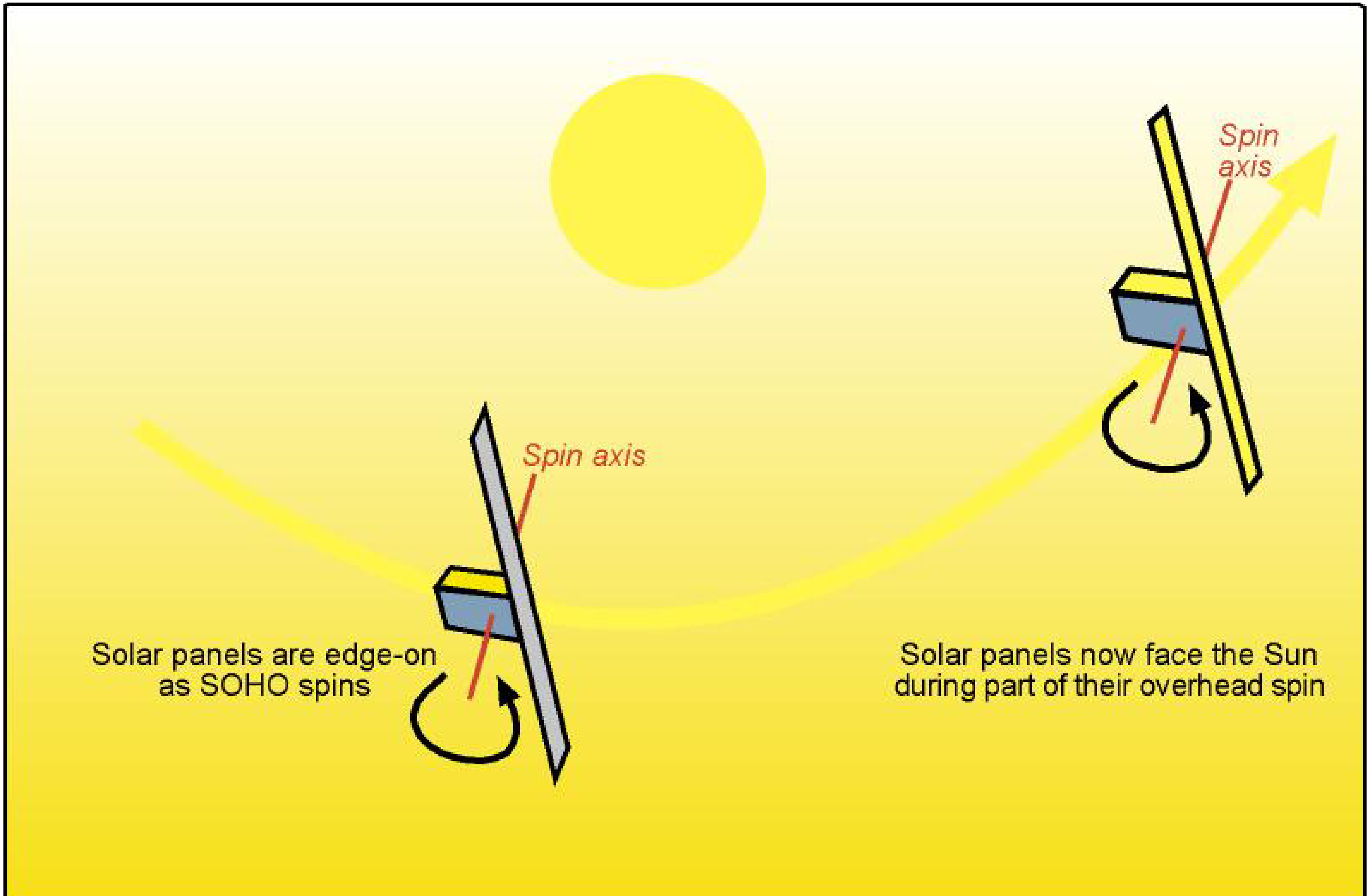
Attitude and Orbit Predictions

- Dynamics analysis and simulations based on the last minutes of telemetry indicated that the S/C was spinning with about 6-8 deg/s.
- Expected to fall into a flat spin around the axis of major inertia (~Z-axis)
- Time scale: ?? (estimates varied from hours to weeks)
- Orbit: was expected to remain stable for a few months, depending on Δv experienced during thruster firings.



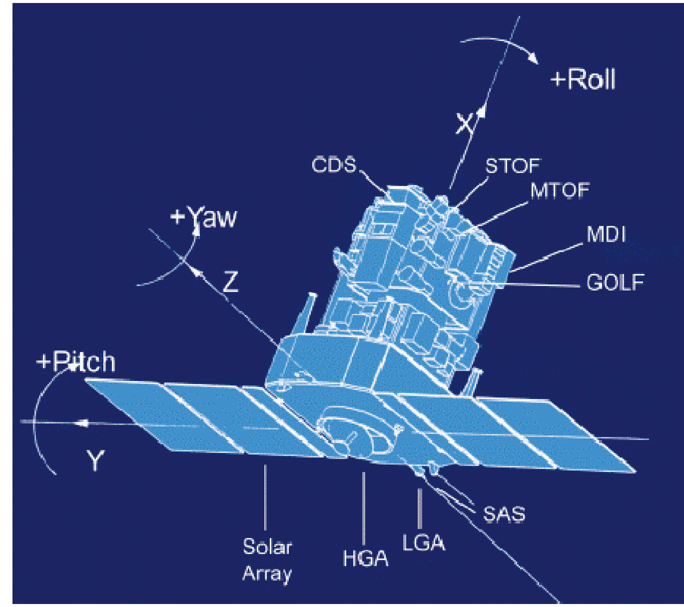


Flat Spin


Spin axis
Spin axis
Solar panels are edge-on as SOHO spins
Solar panels now face the Sun during part of their overhead spin

Uncertainties

- How much thruster firings after loss of telemetry?
  - ESR controller on when power is available
- On which side did the S/C fall? +Z or -Z?
  - Which Low Gain Antenna visible from Earth? The one connected to the “good” receiver?
  - Temperature of different instruments and subsystems either very cold (< -100º C) or very hot (> +100º C)
- What is the temperature of the receiver and transmitter?
  - What is the exact up/down link frequency?
- Developed different strategies to sweep/step up both up- and downlink frequencies.
- Spectrum analyzers were installed at DSN and ESA stations to detect any spike of the downlink carrier.
- Used the digital SETI Wide Band Spectrum Analyzer to search for SOHO signal.



No signal from SOHO

Three long weeks later …

with no signal from SOHO

The search continues ...

- Daily Status Updates on SOHO home page got a bit “terse”.

15 July 1998

The search continues.

A system is being installed which allows to view the spectrum of the downlink in real time at the EOF.

DSN coverage:

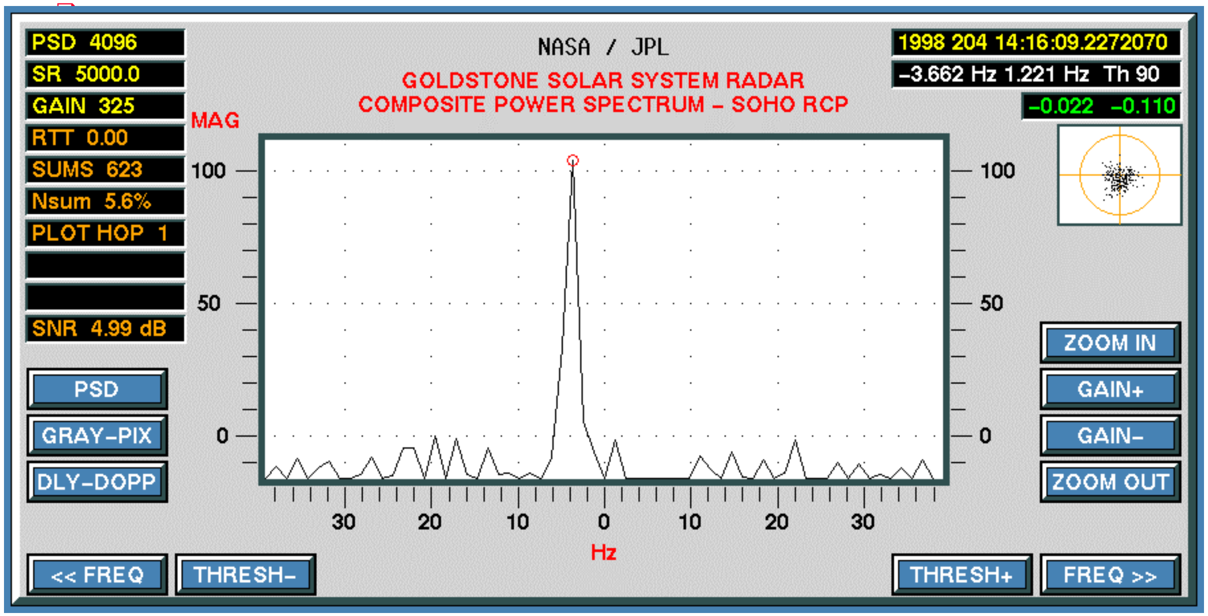
Date	DOY	Time	Station
15/7	196	0010 - 0420	DSS42 Canberra
15/7	196	0755 - 1135	DSS61 Madrid
15/7	196	1155 - 1445	DSS24 Goldstone
15/7	196	2100 - 0245/197	DSS42 Canberra

- Dave Israel (GSFC) developed a program to view the output from the spectrum analyzers at the DSN and ESA ground stations in real-time at the EOF (over the Internet). This feature was of crucial importance later during the recovery.

Arecibo Radar Measurements

- Friday, 17 July, 4pm EDT Alan Kiplinger (Univ. of Colorado) called and suggested to use Arecibo radar to search for SOHO.
- Friday, 17 July, 4:15 pm Donald Campbell (NAIC/Cornell) contacted.
  - first estimates indicated that it didn't seem completely unfeasible
- Sunday, 19 July, Donald Campbell flew down to Puerto Rico
- Arecibo optimized for planetary radar measurements
  - Difficulty to swap 1-ton transmitter and receiver in 5 sec intervals
  - Decided to first try a bi-static radar measurement Arecibo - SOHO - Goldstone

SOHO Detected by Arecibo Radar on Thursday, 23 July 1998



- strong echo after 5 min

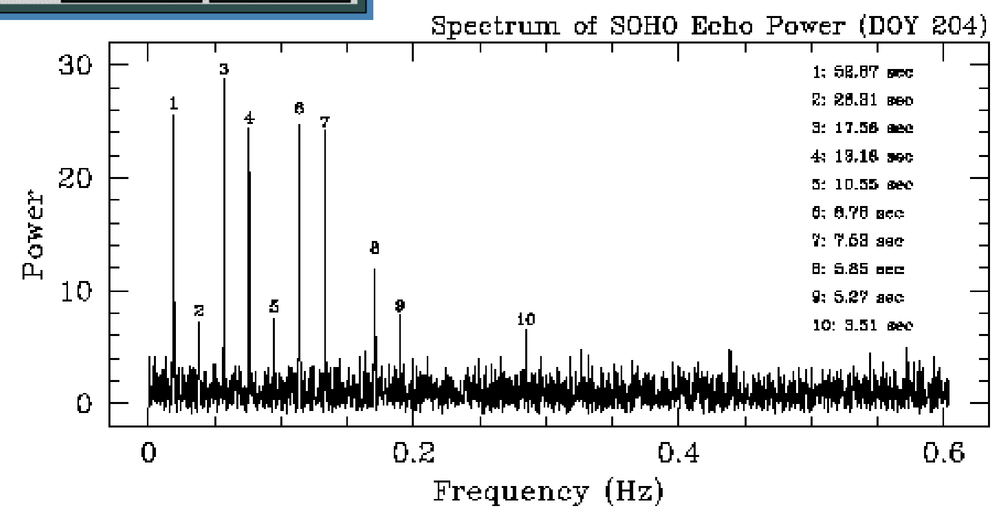
⇒ still at expected position

- narrow line width

⇒ not spinning excessively fast

2 weeks later: rotation period from detailed analysis of light curve:

$$P \approx 53 \text{ sec}$$



NAIC Arecibo / JPL Goldstone Solar System Radar

Gregory Black (NAIC)

Getting SOHO to Respond

- Commands were continuously being sent toward SOHO to respond.
- On August 3, 22:51 UT, 40 days after the loss of contact and after trying 37 different command procedures to switch on the transmitter, spikes in the downlink were detected both by the DSN station at Canberra and ESA's Perth station.
- The spikes lasted between 2 - 10 seconds
  - time left with power on the S/C bus after the 10-12 sec required for reboot of basic on-board computer and switch on of transmitter
- Only carrier signal, no information yet.
- SOHO was still capable of receiving and responding to ground commands!

SOHO was alive!

First Frames of Telemetry

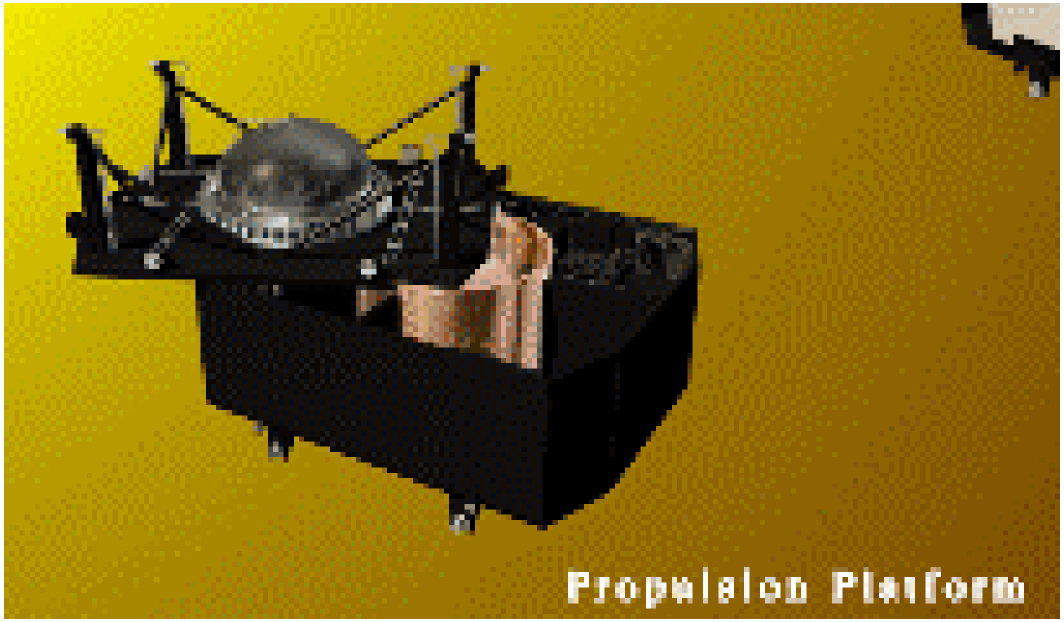
- Next challenge: acquire and decode the telemetry.
- Proved to be impossible to lock long enough on signal to decode telemetry.
  - 1 frame is 15 sec, and the digital boxes required several frames to lock on signal.
  - Considered to dig out and install the old analogue tape recorders at DSN stations.
- On August 8 (5 days after we first saw the carrier), we succeeded to charge up one battery after 10 hours of continuous commanding in the blind to force the Battery Charge Regulators ON.
- 7 frames of housekeeping telemetry were received.
- Telemetry data confirmed:
  - rotation period of 52.6 seconds (spin rate: 6.8deg/s), +Z axis facing the sun
  - some instruments very hot (>+80ºC), others very cold (<-60ºC)
  - deep cold conditions of most of the service module equipment
  - hydrazine tank partially frozen (at ~1ºC), pipes and thruster frozen (-16º to -35ºC)

Charging the Batteries

- Due to S/C rotation, the batteries were in charge only 45% of the time
- They would charge eventually, if the total power consumption stayed below 67 W
- But to switch ON telemetry consumed 105 W!
  - Battery management would be a challenge
  - Had to work in the blind for most of the time

Thawing the Tank

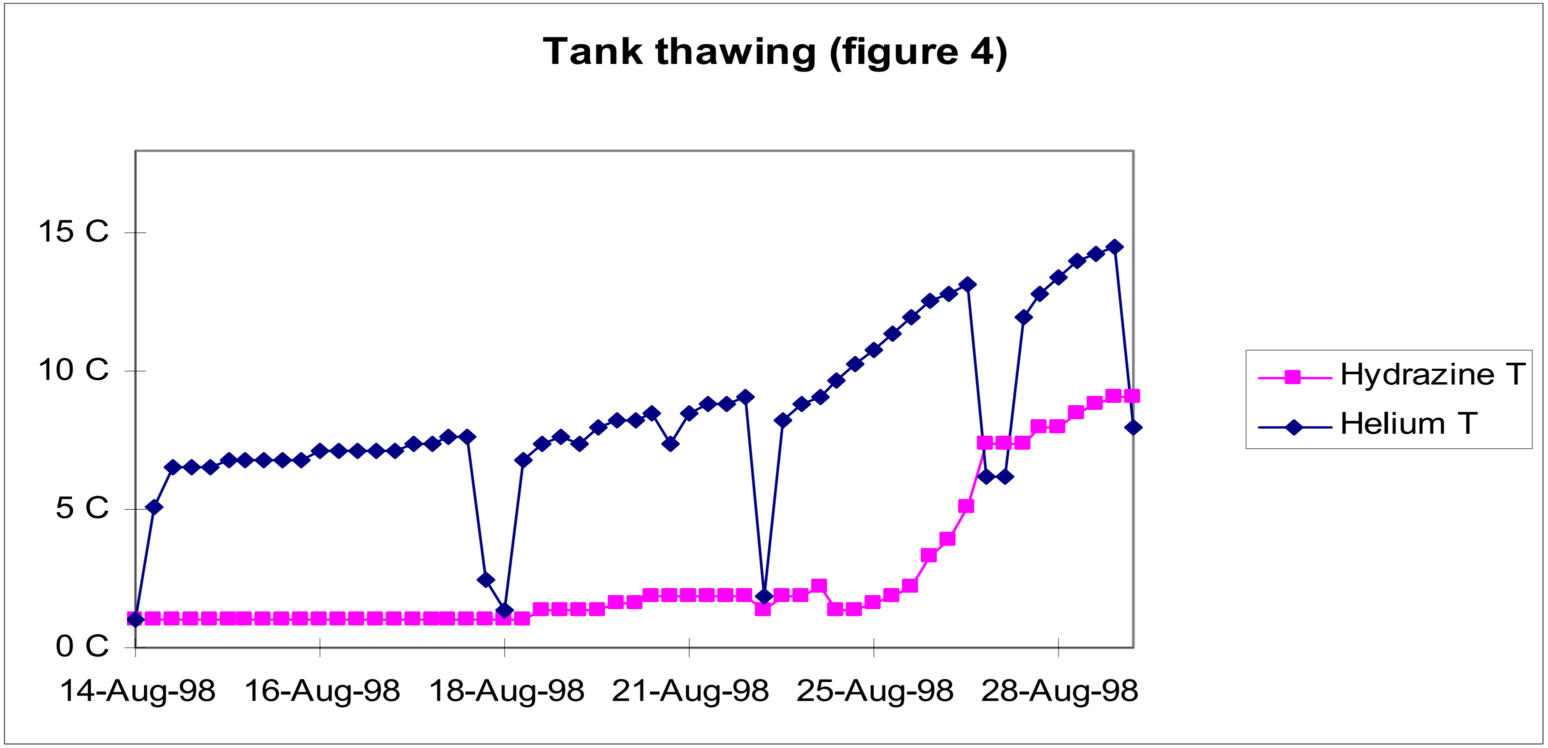
- Next challenge: thawing of the hydrazine in the tank, associated pipes and thrusters.



- From thermal models: at least 48 kg of the 200 kg of hydrazine frozen.
- First the tank, then pipes and finally thrusters, to allow any overpressure of thawed hydrazine to flow back to the tank through liquid lines.
- Tank thawing was started on 12 August.

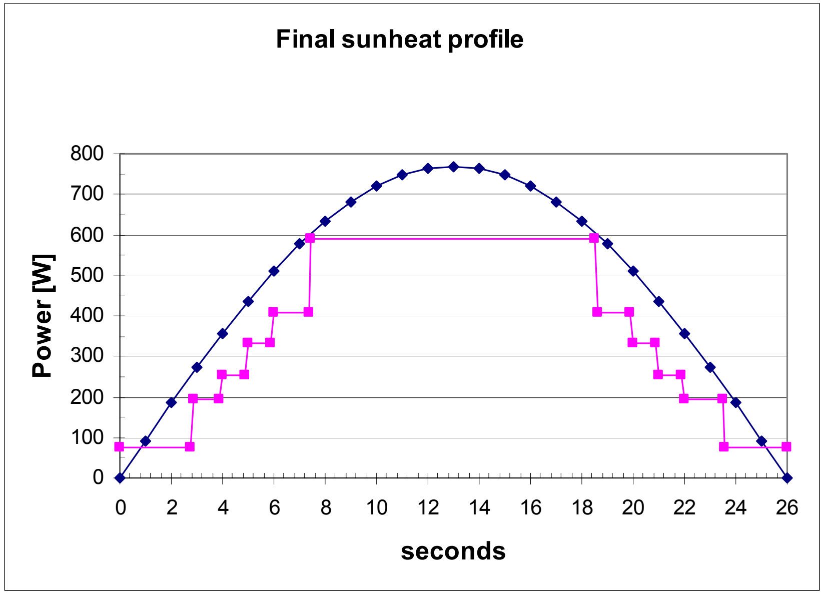
Thawing the Tank

- Heating power: 32 W
- 3 interruptions to recharge batteries
- Total duration of heating: 11 days (275 h)



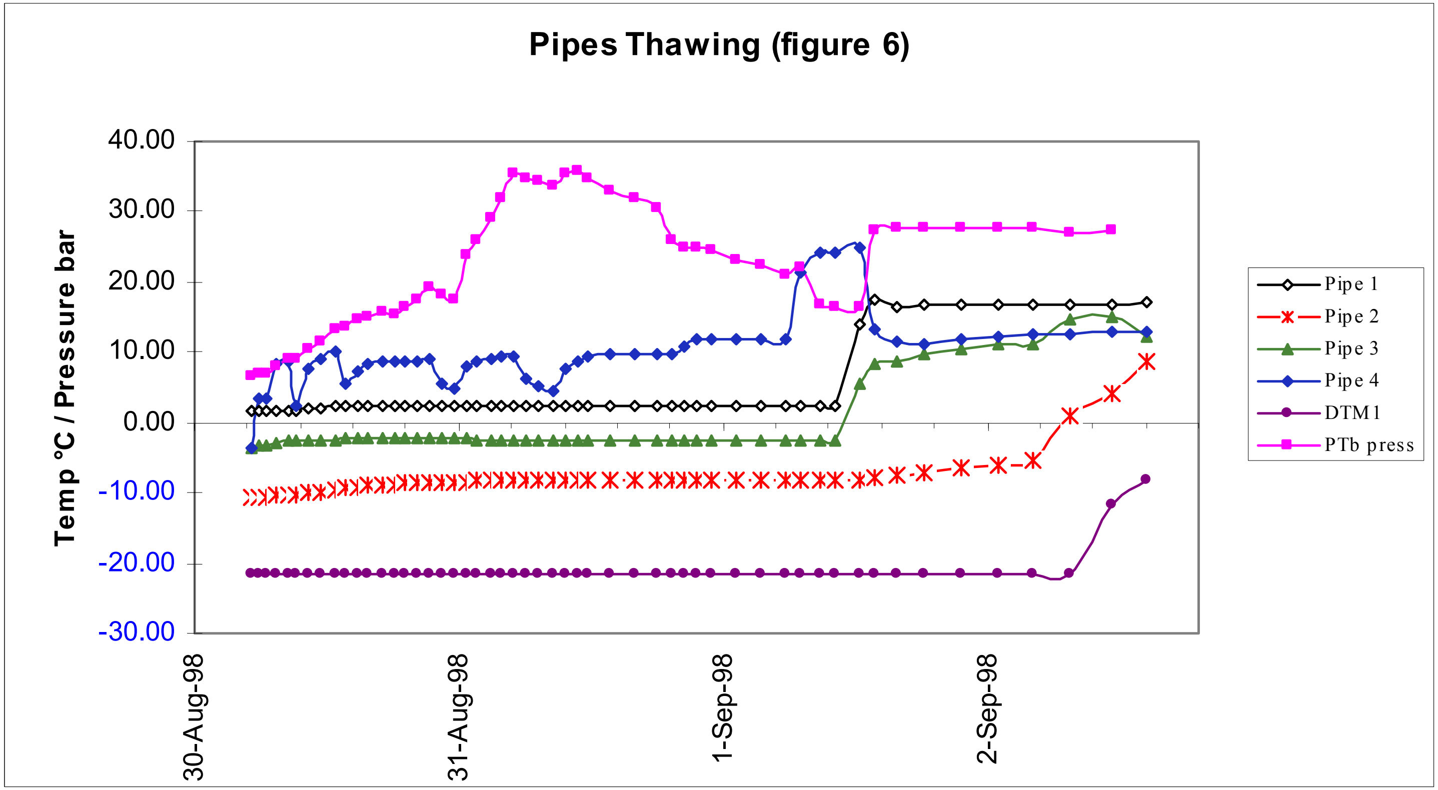
The “Sunheat” Mode

- During the heating of the pipes and thrusters the heating of the tank had to be maintained which consumed more power than available.
- Patch of the Central Onboard Software to use solar array current like a “fake thermistor” in order to switch ON heaters only when power was available from the solar arrays (Francis Dufrechou, MMS).
  - Heaters ON only when current was above a maximum selected so that heating did not discharge batteries.
- Several “tunings” of this mode
- Final version: sequential switch on of heaters
- Peak power: > 500 W



Thawing the Pipes

- "Sunheat" mode proved to be critically important for keeping the pipes and the tank from freezing without discharging the batteries while heating thrusters.
- Thawing of the pipes was achieved on Sept 3.



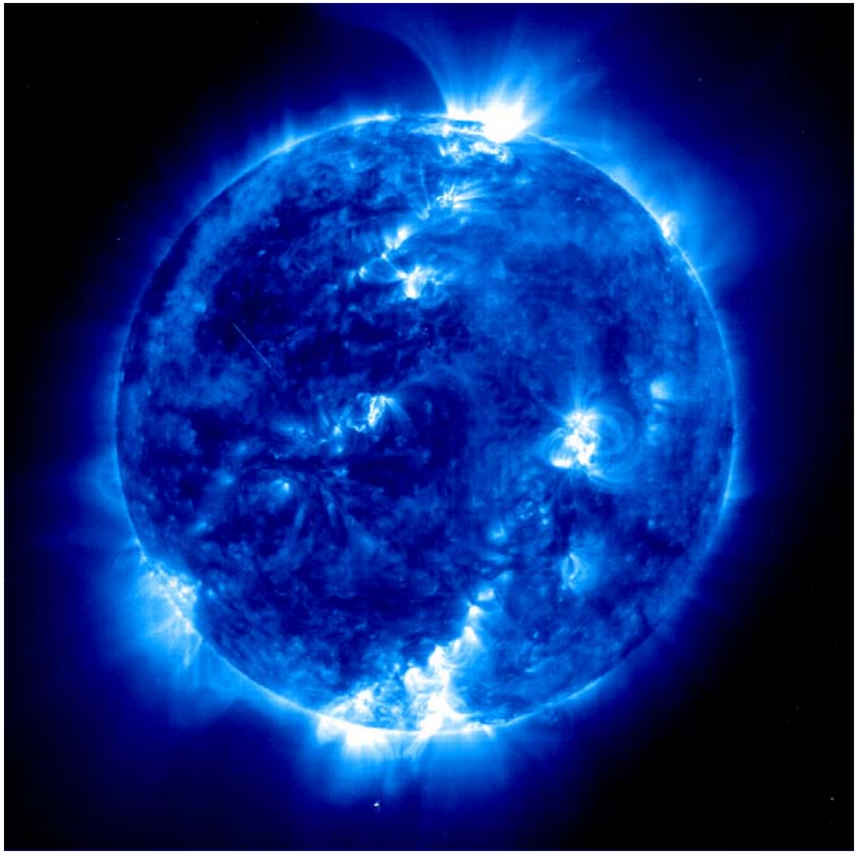
Solutions to Recover Sun-pointing Attitude

- It was impossible to thaw the entire propulsion sub-system. Two of the thrusters and their associated pipes were still frozen.
- Four attitude recovery maneuvers were studied
- The one finally selected was:
  - a Z-axis de-spin followed by a triggering of an Emergency Sun Reacquisition (ESR) without roll control (without using thrusters not completely thawed)

D-Day: 16 Sep 1998

S/C and Instrument Re-commissioning

- Spacecraft status after the recovery and 3-week re-commissioning
  - All subsystems OK, except two of the three gyros
- Instrument re-commissioning
  - Instruments experienced < -120º to > +100º C!
  - Re-commissioning started on 5 October and was completed on 5 November
  - Miraculously, all the instruments worked (except innermost coronagraph of LASCO)
- More than 94,000 (!) commands were sent to S/C and instruments during recovery



FIRST IMAGE from EIT on 13 Oct 98

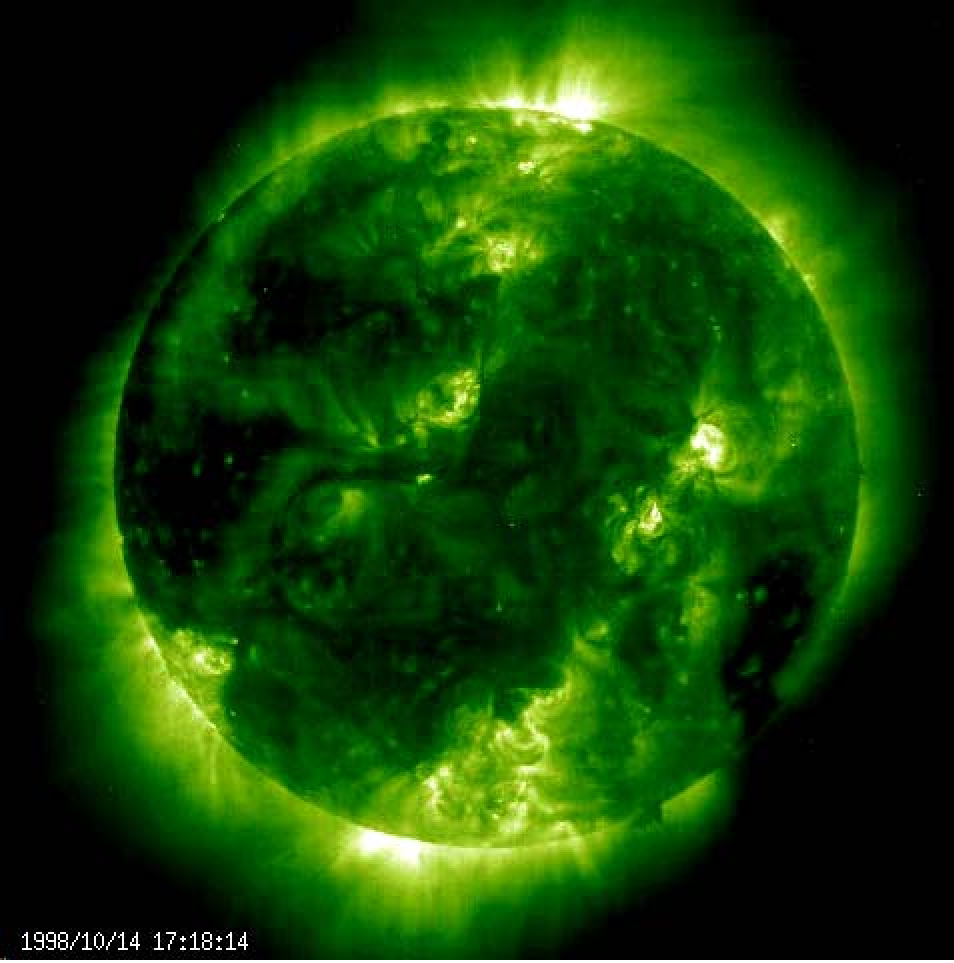
SOHO's Tribulations not over yet ...

- On 21 December, the last gyro failed during the preparation of a routine orbit correction
  - SOHO went into ESR again (with roll control from ground)
  - Keeping the spacecraft pointing to the Sun consumed about 7-9 kg fuel per week
  - Needed to develop urgently software patch which would allow to exit ESR without gyroscopes
- SOHO back in normal mode on 1 February 1999
- Spring-summer '99: Development of a completely new attitude control software for gyroless operation.
- New gyroless software uplinked and commissioned in Sept 1999
  - Much more robust operations
- This made SOHO the first three-axis-stabilized spacecraft to be operated without a gyro.

Recovery Team

- More than 160 people (from ESA, MMS, NASA, ATSC, CSC, DSN, NAIC, ...) were involved in the SOHO recovery.

We did it!



Your magnificent success and candit postings have re-energized my interest in human space exploration. Thank you again for the great drama – perhaps the Internet's best moment to date.

“There are no miracles, only hard work”

Roger Bonnet

15 September 1998

Citation of IAA
Laurel for Team Achievements Award

To the team of scientists, engineers and managers for the development and operation of a world-class mission leading to substantial advancements in understanding the Sun and the solar-terrestrial relationship.